Quantitative Estimation of Variability in the Underwater Radiance Distribution (radcam)

Marlon R. Lewis
Satlantic, Inc.
Richmond Terminal, Pier 9, 3481 North Marginal Road
Halifax, Nova Scotia, Canada B3K 5X8
phone: (902) 492-4780 fax: (902) 492-4781 email: marlon@satlantic.com

Scott D. McLean
Satlantic, Inc.
Richmond Terminal, Pier 9, 3481 North Marginal Road
Halifax, Nova Scotia, Canada B3K 5X8
phone: (902) 492-4780 fax: (902) 492-4781 email: marlon@satlantic.com

Award Number: N00014-07-C0139
http://www.satlantic.com

LONG-TERM GOALS

A significant source of uncertainty in the prediction of the apparent optical properties of the ocean is the geometrical distribution of the radiance field and its variation with respect to time and space; this uncertainty directly affects attempts to use measurements of reflectance and attenuation for the diagnosis of ocean constituents. Uncertainties in the time and depth dependent variations in the radiance distribution, and their sources of variation, propagate as well to the prediction of the performance of new imaging systems such as the "virtual periscope". The problem starts at the sea surface, where the generally unknown sky radiance distribution, coupled with a roughened air-sea interface, plays a major role in the transmission of sun and sky radiance to below the surface. In the ocean interior, the volume scattering function, and the absorption coefficient alter the radiance distribution in both the forward and backward direction; in the perhaps usual situation of multiple scattering, the uncertainty in the radiance distribution becomes large. In optically shallow areas, non-Lambertian bottom reflectances add to the uncertainty.

Our long-term goal is to develop and deploy a relatively simple means for the measurement of the full radiance distribution, which could be routinely deployed by the optical oceanographic community. A further side benefit would be that many of the measurements currently made, such as planar and scalar irradiance, angle-dependent Q factor etc., could be made by various integration operations on the measured radiance field rather than with mechanical diffusers. The potential interferences of various deployment platforms (e.g. shading, reflectances by ships, buoys and towers) could be measured directly rather than inferred based on inaccurate assumptions about the underwater radiance distribution. A direct confirmation of the asymptotic radiance distribution can be made. Finally, high quality quantitative (and radiometrically calibrated) measurements of the radiance distribution, and their time and depth derivatives, can in principle (but not yet in practice) be used to estimate all the inherent optical properties (both absorption and volume scattering coefficient) and as well the nature of the air-sea interface.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
30 SEP 2008	**Annual**	**00-00-2008 to 00-00-2008**

4. TITLE AND SUBTITLE
Quantitative Estimation Of Variability In The Underwater Radiance Distribution (radcam)

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Satlantic, Inc.,Richmond Terminal, Pier 9,3481 North Marginal Road,Halifax, Nova Scotia, Canada B3K 5X8,

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
code 1 only

14. ABSTRACT
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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

OBJECTIVES

The Radiance Camera or RadCam project is part of the Radiance in a Dynamic Ocean (RaDyO) program. The primary objective is to create a camera that can record the spatial radiance distribution at the ocean surface and at depth. The proposed instrument will be uniquely capable of resolving both the downwelling and upwelling radiance distribution and its variation with depth, time and wavelength ($L(z,t,\theta,\phi,\lambda)$); from these measurements, the apparent optical properties E_D, E_U, E_o, E_{ou} and E_{od} are computed by integration. The distribution functions (e.g. the average cosines) are computed directly, as are the various diffuse attenuation coefficients and reflectances. The fully-specified radiance field therefore provides all the pertinent information to derive not only the apparent optical properties, but the inherent optical properties: the absorption coefficient and, in principle by inversion, the volume scattering function. An instrument capable of this measurement to the necessary accuracy, resolution, and noise characteristics could, again in principle, replace all or most of the optical instruments currently deployed today.

APPROACH

While radiance cameras have been built before, they have not been able to image the sun at the surface due to the very high scene dynamic range. RadCam will take advantage of recent developments in high-dynamic range (HDR) CMOS imaging arrays. These arrays were developed for science, surveillance, and automotive applications. Traditional CCD arrays are linear, limiting the dynamic range that can be achieved. These HDR CMOS arrays use a number of different methods to produce a nonlinear response function, giving scene dynamic ranges of up to 120 dB or 6 decades.

WORK COMPLETED

In the first year of this project we considered several possible cameras and imaging arrays. We tested two candidate cameras/arrays and selected one for RadCam. Measurements showed operate with a scene dynamic range of 6 decades and an impressive system dynamic range of nearly 10 decades.

Three instruments are being designed as part of this project. The first is a reference camera that will be mounted on deck. The second is a logging-type instrument that can be mounted on a Bluefin AUV or an ROV. The third is a profiler that sends data to the surface for real-time processing. The first two cameras are upward looking only (i.e. they record downwelling radiance) while the profiler has both an upwelling and downwelling camera. This allows it to measure radiance over the entire sphere around the instrument.

During the second project year the first two cameras were assembled. They were then tested at a RaDyO field experiment at Scripps Pier in January 2008. Following that, the profiling camera system was designed and built. All three cameras were then tested at a second RaDyO field experiment in Santa Barbara Channel in September, 2008.

RESULTS

Hardware

Each of the cameras include a bandpass filter centered at 555 nm with a 20 nm bandwidth. The imaging chip is a very high dynamic range CMOS array. The scene dynamic range is 10^6 and the system dynamic range is nearly 10^{10}. The high scene dynamic range allows the sky and near surface radiance fields to be measured without needing to block the sun; the sun does not saturate the array or cause blooming. The field of view of each camera is 180 degrees. The resolution is 0.5 degrees on axis and drops to about 1 degree at large field angles. The frame rate is better than 7.5 fps, limited by the deck computer and software that records the video.

Three RadCam instruments are now in operation, as shown in Figure *1*. All instruments contain the same high-dynamic range camera, but the reference camera is without a glass dome to reduce glare. It is designed to be mounted in a tripod or attached to a vertical pole. It transmits live video via a fiber optic cable. Like the other cameras it includes a tilt sensor and compass to orient the images to a fixed coordinate system. The second camera is designed to fit in a Bluefin AUV, but can also be mounted in its own cage and lowered from a winch. It logs all data internally but can be cabled with a low-speed Ethernet connection to provide a subsample of the video in near-real time over a virtual network connection.

The profiling system consists of both a downwelling and an upwelling camera, and ancillary sensors including a Falmouth Scientific CTD, multispectral radiance-irradiance head from Satlantic, and a Wetlabs transmissometer. It uses a fiber optic cable to transmit real-time video to the surface. It is designed to freefall through the water column. Optimization of the profiler ballasting is still underway but the tilts are generally less than 3 degrees and fall rates can be controlled from 0.3 to 1.0 m/s. We have also performed some fixed depth measurements with the profiler using a tethered float.

Initial Data

An example of the underwater light field on an exceptionally calm, sunny day is shown in Figure *2*. The images are uncalibrated, but nicely show the Snell cone within the overall 180 degree field. Due to refraction, the Snell cone images the entire hemisphere above the water's surface. Although the sun is only a couple pixels in diameter, the bright area around the sun is much larger, in part due to scattering in the optical system. The noisy appearance of this region is because at those grayscale levels, the slope of the response curve is steep, and there is large variation from pixel-to-pixel. This will be removed after calibration. Finally, the bright rings outside the image area are also caused by scattering.

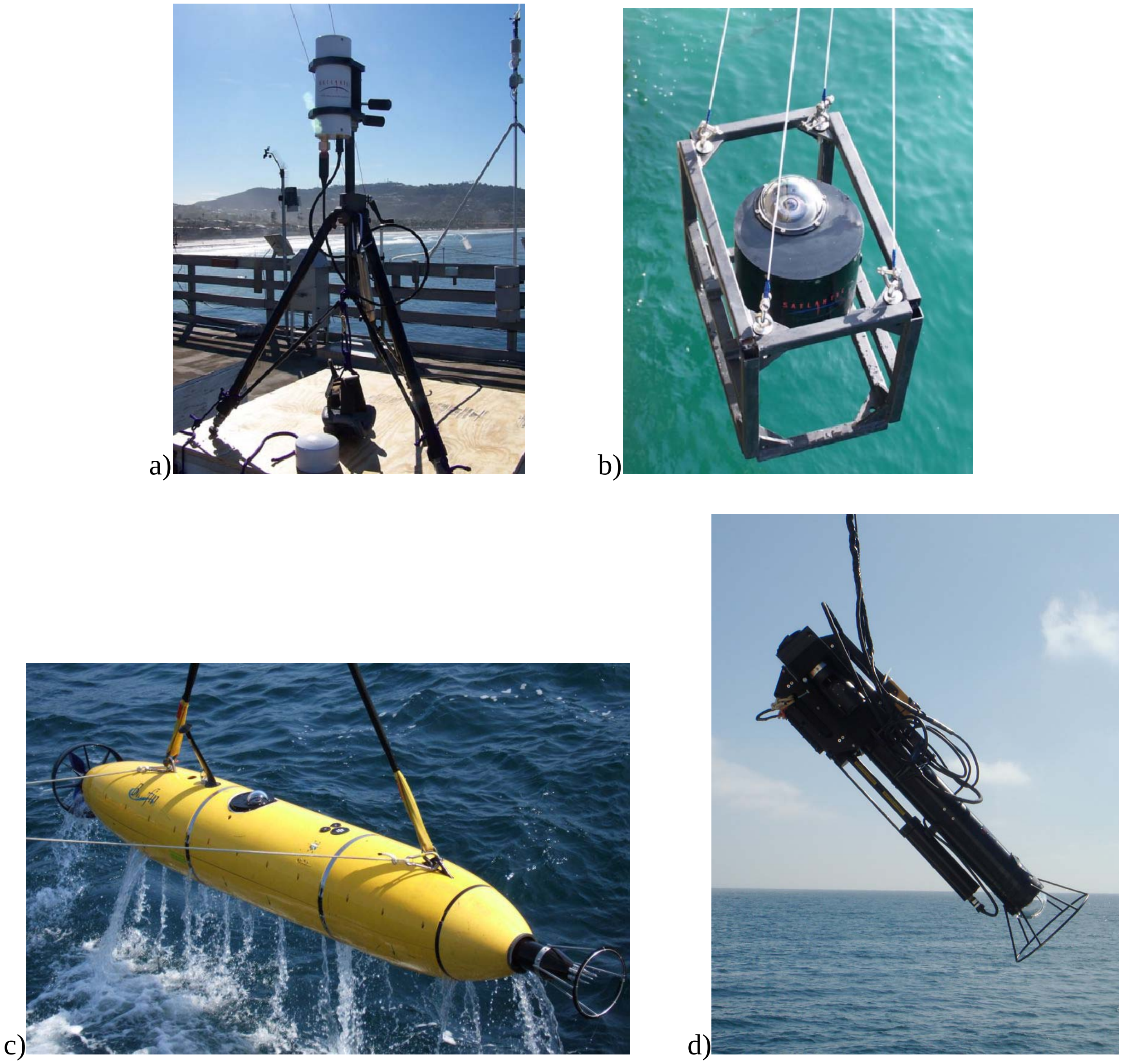

Figure 1: Photographs of three RadCam instruments are a) the in-air reference camera mounted on a tripod on the roof of the lab on the pier at Scripps, b) the logging camera mounted on a cage and being lowered into the water c) the logging camera mounted on an AUV (center of Bluefin) and d) the profiler camera system hanging from the wire as it is being deployed in the ocean off Santa Barbara, CA.

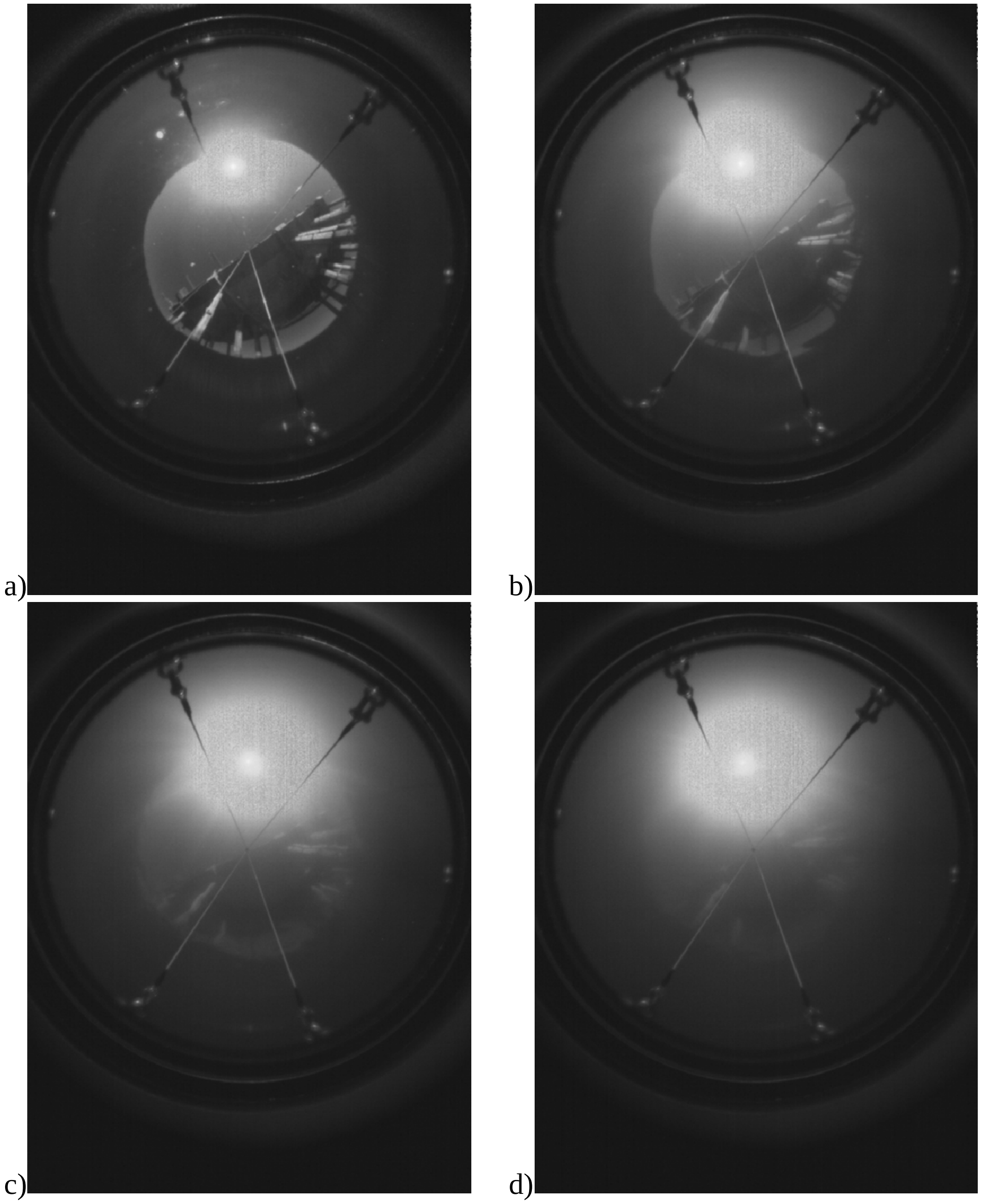

Figure 2: Downwelling light field at Scripps pier with exceptionally calm surface conditions. The series was taken using the ROV camera mounted in a cage hung from a bridle. The depths are a) 50 cm, b) 150 cm, c) 250 cm, and d) 350 cm. The images becomes progressively diffused, as does the edge of the Snell Cone.

Figure 3 shows one of a sequence of frames recorded with the downwelling (upward looking) camera from the Profiler RadCam. The conditions were overcast with light winds and calm surface conditions. At the edges of the Snell cone, the waves produce a high contrast pattern.

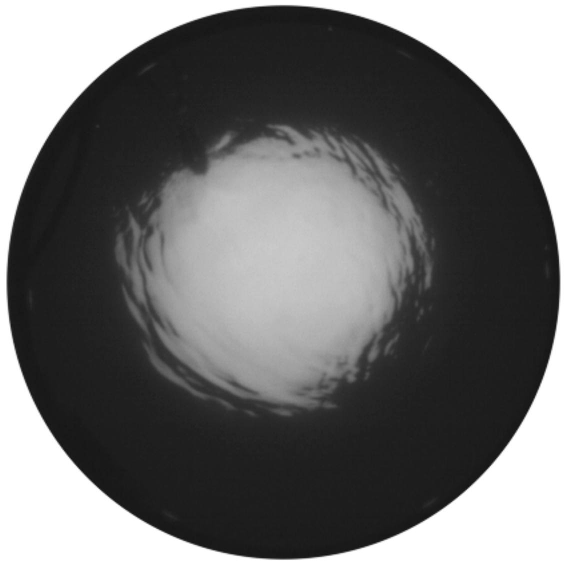

Figure 3: Downwelling light field on an overcast day at a depth of 1m, showing details of the wave field.

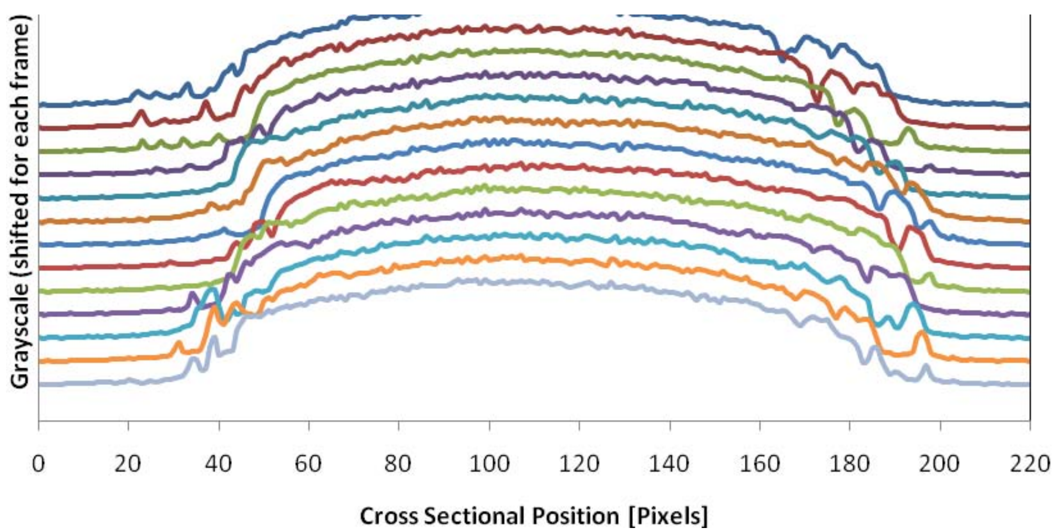

Figure 4: Simple representation of the light field variation across the Snell cone, showing fluctuations near the boundary due to waves and their evolution over time.

In *Figure 4*, we plot grayscale along a cross section through the Snell cone over successive frames. Lower curves are increasing time, 0.125s between frames. Note that the grayscale to radiance relationship is nonlinear for our imaging array, and that the changing tilt of the camera over time has not been considered. The contrasting light and dark bands, due to waves, can be seen to propagate over time. With a more thorough analysis, this detail can be used to derive an approximation of the surface wave field.

Calibration

Calibration of the cameras consists of measuring the response function of the array to incident light and then calibrating the whole optical system to a known radiance. The response function is challenging due to both the high dynamic range and the high radiances involved. The response functions are highly nonlinear and vary from pixel to pixel, so every calibration data must be obtained for each pixel. Calibration data has been collected for all of the cameras and is being processed at this time.

Scattering in the optical system must also be characterized by measuring the point spread function (PSF). We are preparing to do these measurements shortly. The entire image processing procedure will then be to apply calibration, deconvolve the images using the PSF, and finally correcting for tilt and heading changes.

IMPACT/APPLICATIONS

The camera may have applications for various sorts of surveillance. Radiometrically calibrated measurements of the in-air and in-water radiance distribution can be made. The derivation of optical properties from these measurements may have practical applications. The shading effect of deployment platforms can be studied directly.

RELATED PROJECTS

This project is embedded within the Radiance in a Dynamic Ocean (RaDyO) program, and hence is related to all projects contained therein. It is also related to the research programs of Dr. John Cullen, some of which are sponsored by ONR. Lewis has related projects funded through Dalhousie, and Lewis and McLean have related NASA-funded efforts through WetSat Inc.

HONORS/AWARDS/PRIZES

Lewis, M.R.: Awarded Killam Professor of Oceanography, Dalhousie University, Killam Foundation.